percent decrease in the chloride concentration in the 5–10-cm. soil interval. This could have been caused by condensation of water vapor that diffused downward from the warmer surface soil. The condensate would dilute the soil solution. However, the upward flow of film water in response to the suction gradient dominated the water transport processes in the 5–10-cm. soil interval and was the mechanism responsible for the movement of salt to the surface.

moisture—
depth percentage

Retention curves showing the change in water content of soil cores as the suction is increased from zero to 15 atmospheres.

The hypothesis that the readiness with which plants can absorb water from soil is measured directly by suction or suction head has evolved over a period of years. The evidence supporting the hypothesis has been reviewed in the monograph of the American Society of Agronomy, *Soil Physical Conditions and Plant Growth.* The usefulness and significance of moisture retention curves as they relate to this hypothesis is at once apparent.

The foregoing discussion in terms of hydraulics has omitted complicating factors, such as capillary hysteresis, temperature, and the effects of soluble and exchangeable ions on the hydraulic properties of soils. For many practical purposes, however, the simplified treatment aids in understanding and quantitatively expressing observed phenomena relating to the retention and transmission of water by soil.

L. A. Richards *has been interested in the scientific aspects of soil water since early in his undergraduate work at the Utah State Agricultural College. He received the Ph. D. degree in physics from Cornell University in 1931 and spent 4 years teaching physics and conducting research in soil physics at Iowa State College. He has been soil physicist of the United States Salinity Laboratory, Riverside, Calif., since 1939.*

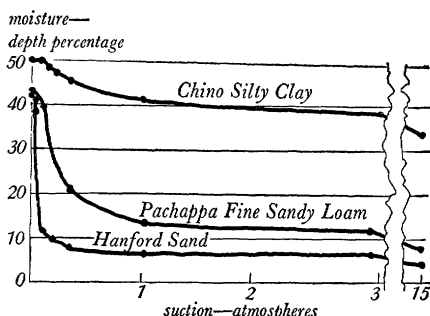# How Much
of the Rain
Enters the Soil?

G. W. Musgrave

What really counts in a rain is how much of it enters the soil.

The nature of the soil, its condition, the nature of the storm, and the season of the year determine infiltration, the amount of water taken in by the soil.

Infiltration tends to be higher in the warm months than in the cool months. Wide differences in infiltration occur in row crops, pastures, and hayfields.

On the Middle Branch of Westfield River at Goss Heights, Mass., the average annual amount of intake is 19.6 inches—or about 43 percent of the annual rainfall. On the Red River at Fargo, N. Dak., it is 19.7 inches— or about 94 percent of the annual rainfall. On the Pearl River at Edinburg, Miss., it is nearly twice as much, 38.8 inches, which is about 70 percent of the rainfall. In some parts of the Southwest the annual runoff averages less than 0.01 inch, but there the rainfall is also low. Those results are from relatively large watersheds, which have different soils and vegetation.

It is not easy to measure infiltration accurately. Several methods are available, but some are not entirely reliable. On large watersheds it is customary to take the difference between rainfall and runoff as an index of intake. But that is not strictly accurate, because

such calculations include the amount of rainfall that wets the vegetation and the ground surface and fills the many small depressions found in any locality. Near the end of a big storm, however, after the depressions have been filled and the entire area has been soaked, the difference between rainfall and runoff closely represents intake.

In places where rates of rainfall and rates of runoff are measured, we can determine the rate of infiltration.

Storms suited to such measurement are uncommon; most storms have high and low intensities of rainfall at different times and in different places on large watersheds. This method is not well adapted to a comparison of soils and vegetation, because most watersheds have more than one kind of soil and vegetation. Unless several recording gages are used on the watershed, the true amount of rain falling on each part is not known.

To overcome some of the difficulties, equipment has been designed that will provide artificial rainfall, uniform in rate and of large amount (since the amount must really test the capacity of the soil). The equipment can be moved from one soil or kind of vegetation to another and thus sample different conditions within a watershed.

Most commonly used is the Type F infiltrometer. A smaller version, the Type FA infiltrometer, is especially useful in localities to which it is difficult to transport the large quantities of water required by the Type F. Both provide raindrops large enough to approximate the surface impact of natural rain. The rainfall is applied at a known rate, and the rate of runoff is measured. From these the rate of intake is calculated.

Water is applied to two of the commonly used types of infiltrometer (tubes and concentric rings) by flooding the soil surface without greatly disturbing the soil structure. The flooding types give consistently higher infiltration than the rainfall types, but the differences are less under dense vegetation than under sparse vegetation.

The different types of infiltrometers are useful in determining the relative differences between the intake of different soils and vegetation. Intake rates often must be learned for areas where facilities for making measurements differ widely. In places where water supplies are limited, one of the smaller infiltrometers, which require a small amount of water, is ordinarily selected. If better quantitative data are needed and facilities permit, the large Type F infiltrometer is ordinarily used.

Comparisons of different types of equipment operated side by side have shown that relative comparisons of soils and vegetation can be obtained from any of them. The comparisons also show that the intake rates are higher from types that apply water by flooding than from types that apply water as artificial rainfall. But they also show that no simple relation exists between the results of different types applied to different soils or vegetation and that no easy way exists of converting the results from one type to equivalent values of another type. Clearly the nature of soil or vegetation is reflected to divergent degrees in the different techniques used for the measurement of intake. That is not surprising, because the full protective effect of vegetation found under rainfall cannot be measured when water is applied by flooding. Yet all of these methods have a place in the evaluation of the factors that affect intake and also in the evaluation of the different parts of a watershed.

Relative values of intake on a watershed are best obtained from the watershed itself. On watersheds for which we have good records of rates of rainfall and rates of runoff, a comparison, storm by storm and hour by hour, gives us results that reflect the rates of intake when wet or dry, the change with season, or the drop toward the end of storms. These intake rates for the watershed also are weighted by the proportions of soils and vegetation occurring in the area. A number of years of records are needed for such deter-

minations so that large storms are included and the effect of seasons and moisture conditions are represented in the records.

Watersheds that do not have records of rates of rainfall and runoff but have only storm totals can be used to determine approximate rates of intake. The difference between total rainfall and runoff, while including some other items, is mostly infiltration. With a large number of records, the average may be estimated as the difference between rainfall and runoff divided by time. Such records are often available, whereas records including rates are seldom available. Average intake rates derived from total rainfall and runoff thus can serve a useful purpose in watershed evaluations.

On the many watersheds for which such records are seldom available, it is possible to map the soils and kinds of vegetation. The infiltration for different soils having various kinds of cover—that is, a soil-cover complex—may be estimated for each combination. Each of the estimates for the areas in the watershed may then be used to calculate "rainfall excess," and those calculations in turn may be combined to estimate the runoff from the entire watershed. The estimates of runoff may be compared with recorded events, and discrepancies in the estimate of infiltration for certain soil-cover complexes can be readjusted so that the actual observed amounts and the computed amounts agree. The estimates of infiltration may then be applied to the watershed having the changed surface condition. Thus we can assess the improved runoff conditions and the amount of reduction in damage therefrom.

On watersheds where no rainfall and runoff information is available, it is necessary sometimes to estimate the rate and amount of infiltration from other sources. A guide for doing so is outlined here.

A given soil-cover complex, when thoroughly wetted by prior rains, has a minimum rate of intake that is reason-

ably constant and reproducible for this condition. Such minimum rates obtained for row crops during the warm months have been determined for many soils and are usable—with other data—in placing the soil-cover complexes in relative order within the continuous array represented by figure 1.
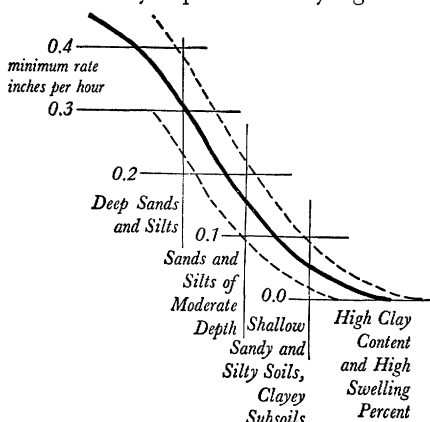
The range of minimum infiltration rates with row crops on wet soils. The variation due to past treatment is shown by the dashed line about the mean.

The chart represents the range for the important soil groups, each with minimum cover and thorough prior wetting, and after a long rain in excess of the infiltration rate. They are thus minimum rates, typical of the growing season of the region. They do not show what happens when the ground is frozen. The broken lines on each side of the curve represent the normal range for the soil-cover complex, which necessarily varies with soil depth, past history of tillage and cropping, and content of organic matter.

THIS ARRAY of soil-cover complexes may be divided into four infiltration groups.

Group A includes the very permeable deep sands and deep aggregated silts of loessial origin; they have little clay and colloid, and the silts have enough organic matter to provide good aggregation.

Group B includes sandy soils and silt loams of moderate depth and above-

average infiltration; the minimum figures for it range from about 0.15 to 0.30 inch an hour.

Group C includes shallow soils in all textural classes; their minimum infiltration rates are below average (0.05 to 0.15 inch an hour).

Group D includes soils with high swelling rates in the surface or subsurface because of high content of clay or colloid; its minimum infiltration rates approximate 0.05 inch an hour.

Each group contains individual units (soil-cover complexes) whose rate of infiltration has been measured by one or more methods. The position of the curve has been determined by minimum rates found on large watersheds. The relative position of the units on the curve has been determined on a comparative basis, for which all available data were considered.

Examples of soils in these soil-cover complexes are given in the table. Since such specific information is not recorded for all soils, the list provides a guide and base points into which other soils may be inserted. Given the texture, soil depth, and other characteristics of soils M and N, a technician ascertains the similar characteristics of soil X and then, through interpolation, can properly place the unknown infiltration of soil X in the list of known soils.

Studies of the physical characteristics of soil show that infiltration in surface soils is correlated positively with its content of organic matter, state of aggregation, and amount of large pores, but negatively with the dispersion of particles. In the subsoil it is also correlated positively with content of organic matter and the amount of large pores and negatively with amount of clay and density of the soil horizon.

THE SOIL CHARACTERISTICS that govern infiltration, to repeat, include the primarily physical properties like texture and depth to the slowly permeable horizons. One also has to take into account the prior history of tillage, which strongly affects structure, or the arrangement of soil particles.

Some of our highest rates of infiltration occur on deep silt loams that are highly aggregated and therefore have relatively large pores. Sometimes the aggregates are the size of coarse grains of sand, and the infiltration is like that of coarse sand as long as the structure is aggregated.

Many hazards beset that favorable structure. One of the most common factors is intensive tillage, which breaks up the aggregated soil particles and exhausts organic matter, one of the essentials of aggregate formation.

Rain on bare soil also breaks up soil aggregates, leaving a compact, dense surface layer, through which water can move but slowly. Grass, trees, or straw mulches protect soils from such forces of disintegration and are also sources of organic matter useful in the renewal of good soil structure.

Beneath intertilled crops like corn, cotton, peanuts, potatoes, or soybeans, infiltration is usually much less than beneath grass, trees, or mulches. The gain in infiltration resulting from a change in vegetation is greater quantitatively on deep, permeable soils than on shallow, tight ones. The potentialities for practical improvement are less on the latter.

The data in the second figure were
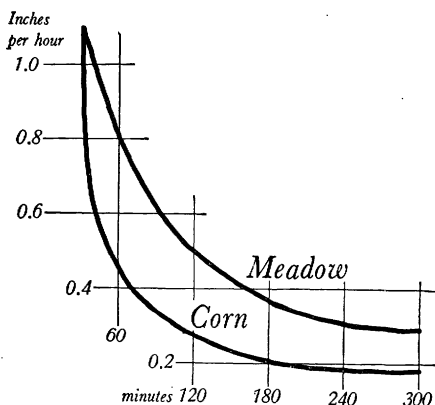
A comparison of infiltration under bluegrass pasture and under corn, showing the more rapid decline in rate for the row crop.

obtained by sampling fields in Illinois where the grass was being grazed and the corn was handled as in normal farm operations. Large and consistent differences occur in the infiltration under corn and under grass. The differences are consistently greater on the deeper soils. Not brought out in the figure itself is the fact that fields that had been in grass for 20 or more years had higher infiltration than fields in grass for 10 to 20 years. The latter, in turn, were higher in infiltration than those that had been in grass 5 years. Clearly the number of years affected the rate; that could come only from residual effects associated with aggregate formation, including primarily an accumulation of organic matter beneath the sod.

Crop rotations are intermediate between grass and corn in effect. The more sod-formers in the rotation, the greater the effect on infiltration—corn, grain, and hay (1 year each) do not affect infiltration so much as does a 4-year rotation of corn, grain, and hay. Small grain also is intermediate between row crops and grass in its effect. Intertilled orchards have a lower infiltration than do orchards in sod.

In estimating infiltration for soils varying from average condition, some further principles should be recognized.

1. Differences in infiltration for different soils are correlated especially well with particle size, amount of organic matter in the soil, and soil depth. These are the main characteristics of a soil to examine in estimating the infiltration.

2. Differences in infiltration for various crops are smaller (a) when the soils approach saturation; (b) when the soils (if they contain considerable clay or colloids) are in their maximum swollen condition; (c) in the cool months rather than the warm months.

3. Different soils must be judged on the basis of their individual physical properties:

(a) Clay soils with a high degree of swelling when wet can be expected to have a much lower rate of intake in this condition than when dry. If cracking is common and extensive when dry, the rate of intake then may be relatively high. (Houston clay is an example.)

(b) Deep sands or soils low in clay and colloid may have rather high rates even when near saturation because swelling is not appreciable. (A deep Norfolk sand is an example.)

(c) Lateritic soils or those from which the colloids have been leached to some extent also tend to retain their initial intake rates after wetting. (The Cecil soils of the Southeastern States, for example, show a relatively slow decline in rate as wetness is increased.)

(d) Soils with water-stable aggregates do not decline in rate so rapidly as those whose aggregated structure is less stable. Silt loams high in organic matter and those of fairly high pH often fall in this class. (An example is the Honeoye series in parts of New York.)
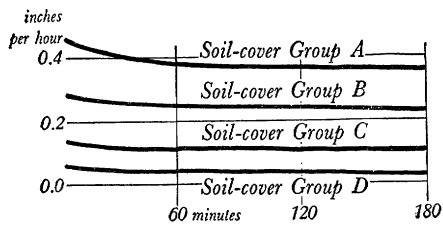
Those relationships govern in principle the shape of the infiltration curve as it declines with time. In figure 3 the decline in rate for a soil in the C hydrologic group is shown for the average moisture and other surface conditions during 149 storms. At 10 hours after start it drops to a near-constant rate of 0.15 inch an hour.
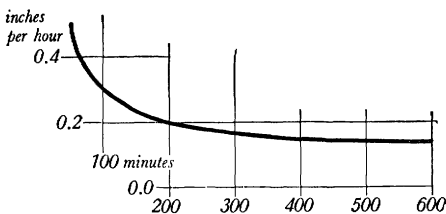
Infiltration under average soil moisture and temperature during 149 storms—row crop, C soil group. (A list of soil groups is given on page 157.)

A second storm on the same soil is charted in figure 4—the intake now, when the soil is thoroughly wet, declines slowly to about 0.10 inch an hour. Typically, the average curve (as in this example) declines rapidly until it becomes nearly asymptotic,

but some further decline occurs in the storm immediately following.

inches per hour

Soil-cover Group A

Soil-cover Group B

Soil-cover Group C

Soil-cover Group D

0.4 — 0.2 — 0.0

60 *minutes* 120 180

Second storms on wet soils of the groups in the first chart. Compare C Group with its average rate shown in the third chart.
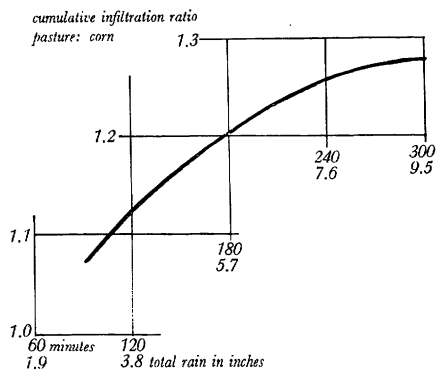
The gain in infiltration that follows a change in vegetation from sparse (as in a row crop such as corn) to dense (as in bluegrass pasture) is shown in figure 5, which is representative of the C hydrologic group. The relative gain is not so great as in that of the B group, where the soil depth may be greater. The gain in sands may be less because no great degree of aggregation follows from the growing of grass. Lateritic soils (such as the Cecil) also may show gains less than that in figure 5, although more than in sands. In the tight clays of the D infiltration group, no large gain occurs from improved vegetation when these soils are swollen and saturated. A factor that affects the amount of gain from grass in the A, B, and C groups (where aggregation is possible) is the age of the sod. Significant positive correlations for 5-, 10-, 15-, and 25-year-old sod indicate that aggregation progressed as organic matter accumulated and as the other processes favoring the formation of large pores had time to become effective.

AN EFFECTIVE WAY to increase infiltration is to use a mulch of straw, crop residues, or other plant materials. At Zanesville, Ohio, an extensive series of experiments were made with different kinds of pretreatment and different kinds and rates of application of mulch. The results showed that the function of the mulch is primarily to protect the existing favorable structure. If the soil

is not permeable, the mulch does not make it so. When a tight soil was cultivated one inch deep and as little as two tons an acre of straw applied to the surface, however, the infiltration rate after 60 minutes of rain was 2.10 inches an hour, and 1.63 inches an hour 100 minutes after the rain started. On land without mulch but otherwise similar in all respects, the rate of infiltration dropped to 0.28 inch an hour within 60 minutes after the start of the rain. The impact of the rain on the unprotected soil produced the typical dense soil surface, which at best is only slowly permeable.

Even stones on the surface may provide some protection. Two plots of Bath flaggy silt loam near Ithaca, N. Y., had a natural cover of small, flat stones. After the stones from one plot were removed, its infiltration dropped greatly below that of the other with its natural stone mulch.

Crop residues of many kinds are used. Tillage practices are being improved so that the subsurface may be broken and a protecting mulch of vegetation left upon the surface. Horticulturists, highway officials, and others sometimes use a burlap cover on steep, newly seeded slopes. Such practices permit improved infiltration, reduce

cumulative infiltration ratio pasture: corn

1.3 — 1.2 — 1.1 — 1.0

240 300
7.6 9.5

180
5.7

60 *minutes* 120
1.9 3.8 *total rain in inches*

The relative infiltration of bluegrass pasture to corn on silt loams of C Group. The relative increase on deep silts may be greater than that shown; the relative increase on sands may be less. Lateritic soils may also be less than that shown by the curve, although greater than for sands.

soil temperatures, and maintain soil moisture at the surface, where germinating seeds can become established.

Fields repeatedly in wheat were investigated at Hays, Kans., and comparisons made between plots on which the stubble was burned before seeding and plots where preseeding tillage was such as to leave the stubble on the surface. The total amount of infiltration during a storm was 0.71 inch where stubble was burned and 1.16 inches where its protecting influence remained at the surface.

The effect of temperature on the rate of infiltration is shown in figure 6, which records a 72-hour test in which soil and water temperatures fluctuated daily more than 20° F., reaching daily the maximum at about 1 p. m. and the minimum at about 6 a. m. The oscillating infiltration curve, if computed

Tentative Array of Soils in order of Minimum Infiltration Rate (Preliminary Grouping) [1]

D—Lowest Group

(Minimum infiltration rate: 0 to 0.05 inch an hour)

Includes soils of high swelling percent, heavy plastic clays, and certain saline soils.

Examples (from low to high):

Houston
Austin
Trinity
Susquehanna
Lufkin
Some gumbos

C—Below Average Group

(Minimum infiltration rate: 0.05 to 0.15 inch an hour)

Includes many clay loams, shallow sandy loams, soils low in organic matter, and soils usually high in clay.

Examples (from low to high):

Bellmont	Berwick	Bates
Bluford	Bogota	Shelby
Cisne	Del Rey	Iredell
Eylar	Atterbury	Elkton
Jacob	Batavia	Vernon
Okaw	Clarksdale	Cecil clay
Racoon	Elliott	loam
Rushville	Shiloh	Dunkirk
Weir	Upshur	Miami
Breese	Putnam	Fillmore
Cowden	Muskingum	Butler
Ebbert	Westmore-	Kirkland
Clarence	land	Rosebud
Patton	Parsons	Myatt
Rantoul	Volusia	Kalmia
Swygert	Viola	Appling
Wabash	Crown heavy	Seneca
Ava	clay	

B—Above-Average Group

(Minimum infiltration rate: 0.15 to 0.30 inch an hour)

Includes shallow loess and sandy loams.

Examples (from low to high):

|		
Arenzville	Melbourne	Tama
Camden	Sylvan-	Orangeburg
Youthful	Blair	Carrington
Ava	Athena	Hopi
Walla Walla	Davidson	Ruston
Sharpsburg	Monona-	Aiken
Selah	Marshall	Hagerstown
Buell	Ida	Hamburg
Badger	Tama	Muscatine
Clinton	Marshall	Saybrook
Colby	Fremont	Harpster
Greenville	Webster-	Ellison
Boone	Clarion	Kincaid
Red Bay	Fayette	Waukesha
Cecil fine	Seaton	Judson
sandy loam	Sylvan	Honcoye
Palouse	Flanagan	Madison
Dubuque	Huntsville	Durham
Kirkland		

A—Highest Group

(Minimum infiltration rate: 0.30 to 0.45 inch an hour)

Includes deep sand, deep loess, aggregated silts

Examples (from low to high):

Knox
Other deep loess
Nebraska Sandhills
Southeast Sandhills

[1] The soils listed have had some measurements of infiltration upon which the tentative array herein is based. It is recognized that some shifting of order is still necessary. Other soils may be added on the basis of the judgment of soils technicians. The names of some of the soils have been changed through recorrelation. The entire list therefore is tentative.
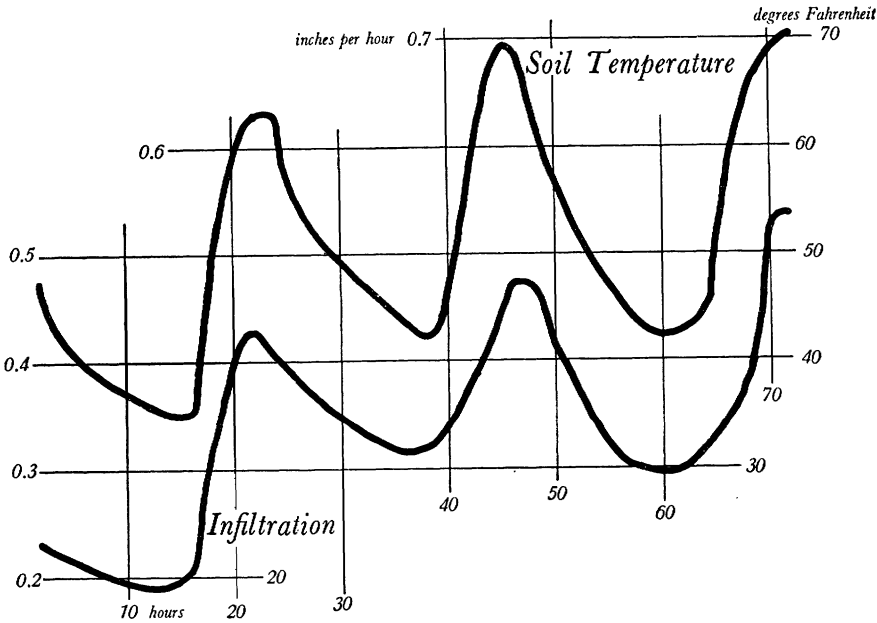
Temperature and infiltration in 72-hour continuous test near Colorado Springs, where infiltration is proportional to viscosity of water.
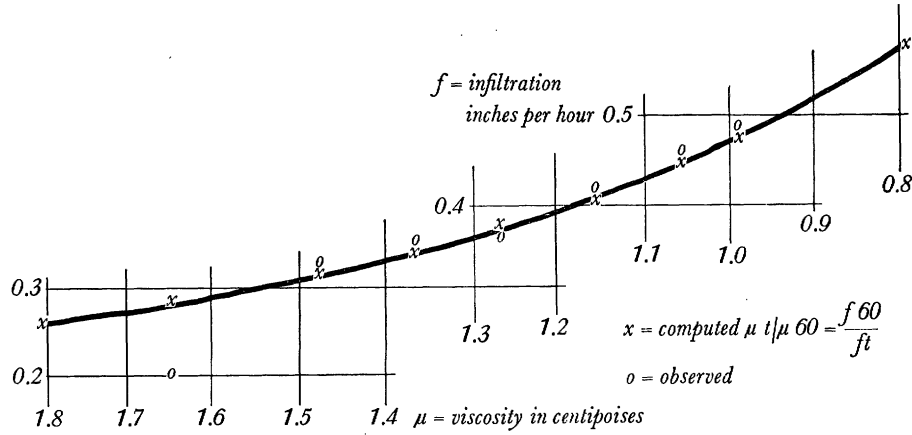
Viscosity of water and rate of infiltration, Colorado Springs, Colorado.

to a constant temperature and viscosity of water, becomes the curve of figure 7, which shows that there is nearly perfect correlation between infiltration and viscosity of water. (A common example of the effect of temperature and viscosity is the flow of molasses, which is much slower when cold than when warm.)

So, in summary, the major factors that affect intake of water by soil are—

(1) surface condition and amount of protection against the impact of rain;

(2) internal characteristics of the soil mass, including pore size, depth or thickness of the permeable portion, degree of swelling of clay and colloids, content of organic matter, and degree of aggregation;

(3) the moisture content and degree of saturation;

(4) the duration of rainfall or application of water;

(5) the season of the year and temperature of soil and water.

Of the five, the ones readily modified by man's action are those dealing with the surface condition of land and its protection against rain impact. Protective covers of vegetation or mulch, with the consequent accumulation of organic matter in the soil, do essentially what Nature has done throughout the centuries. By intensive tillage man disposes of or obliterates the vegetation that provides surface protection and accelerates the loss of organic matter. By crop rotations that include grass and legumes, by continuous or long-time grass crops, and by providing a mulch, he recovers a part of the loss he has caused. Infiltration is improved but not to its full former rate.

For further improvement in intake he looks largely to mechanical means, including terracing, contouring, and various means of retarding surface flow and thus providing more time for the intake of water.

It has been argued that the increased infiltration due to conservation treatment may appear downstream as surface runoff and that this increase may add to the peak discharge. Such a

chance exists, but it is obvious that the movement of water through the soil mantle is slower than its movement across the land surface. The probability that this outflow will be timed perfectly to coincide with the peak discharge of surface flow is quite remote.

Most plantlife is dependent upon the intake of water by soil. Springs, wells, ground-water supplies, and the base flow of streams are dependent on it. To no small degree, man's use and management of the land govern the rate and amount of intake. Fortunately, wise management of land, so that the natural structure of soil is preserved or restored in some measure, is normally beneficial to crop and livestock production, and in addition provides a practical means of supplementing mechanical measures for the reduction of excessive runoff.

G. W. MUSGRAVE *has devoted a large part of his time since 1929 to problems relating to intake of water by soil. As superintendent of the Soil Conservation Experiment Station at Temple, Tex., and later at Clarinda, Iowa, and Bethany, Mo., his attention was directed toward the rainfall that does not run off the land. More recently he has been research specialist dealing with infiltration, and is now staff specialist in the Engineering Division of the Soil Conservation Service.*

For further reference:
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G. R. Free, G. M. Browning, and G. W. Musgrave: *Relative Infiltration and Related Physical Characteristics of Certain Soils,* U. S. D. A. Technical Bulletin 729, 51 pages, 1940.

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1926

1936

These pictures, drawn from photographs, show Lake Como, Hokah, Minn., 4 years after it had been formed by a new dam, and 10 years later, when it had been silted up.